Atom Interferometry with Bose-Einstein Condensates

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The demonstration in 1995 of gaseous Bose-Einstein condensation (BEC) took atomic physics into an exciting new regime in which the motion of large clouds of atoms is clearly governed by quantum, rather than classical, mechanics. All of the atoms in a condensate occupy the ground state of the potential well confining the system, so BEC represents the tightest control possible over matter. This control is at the heart of the field of coherent atom optics, in which the lenses, mirrors, and gratings of light optics are replaced by magnetic or optical potentials, which manipulate the atomic de Broglie wave. Figures 1 and 2 show two examples from our own laboratory of BEC atom optics.

As our next step in this area, we are developing techniques to divide a condensate into two (or more) coherent parts through appropriate manipulation of the confining potential. A division of the matter wave like this is analogous to a beamsplitter in optics. The analogy with optics can be carried further—the process of splitting the condensate (exposing one-half to a perturbation) and then recombining the two parts so that their wave functions can interfere forms an atom interferometer. These devices can respond with extreme sensitivity to any interaction that affects atomic energies. In addition, just as with light optics, the atom optical technology can also be miniaturized ultimately down to the level of an integrated “atom chip” with dimensions of just a few millimeters. Interferometry with BECs might therefore lead to a new generation of miniature sensors having unprecedented sensitivity to electromagnetic fields, to gravity and gravity gradients, and to accelerations. Focusing on just one of these interactions, sensitive instruments for measuring gravity have many important applications, such as underground structure detection; passive navigation and obstacle avoidance for submarines; and location of subterranean deposits of oil, minerals, and water.

Waveguide Interferometry

A simple calculation illustrates the power of atom interferometry—the earth’s gravitational field causes the phase between two rubidium-atom wave packets separated vertically by 1 mm to evolve relative to each other at a rate of 2×10^6 cycles/s. It follows that an interferometer using a condensate of 10^6 atoms would have a statistical sensitivity to $\delta g/g$ of order 10^{-9} if the condensate was split for 1 s. This sensitivity is otherwise reached only by start-of-the-art laboratory instruments that are expensive, complicated, and most definitely not as portable.

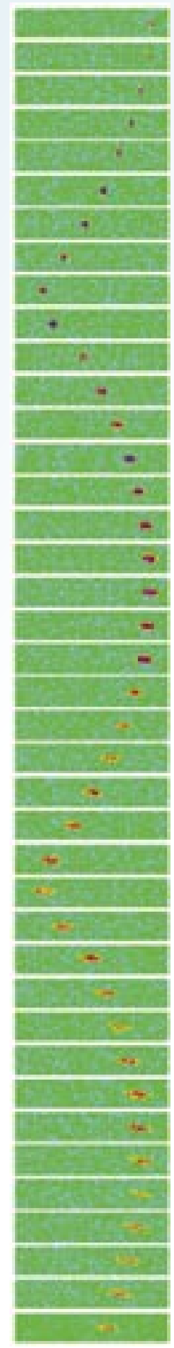
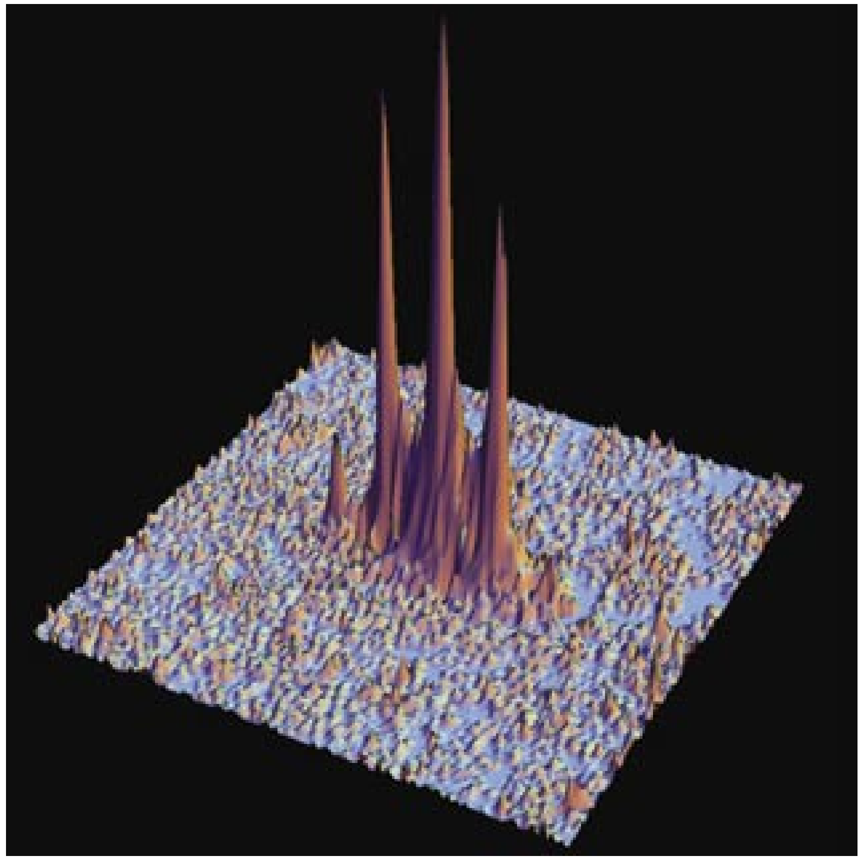


Figure 1. A BEC bouncing on a pulsed magnetic mirror.[1] The anisotropic expansion (fast in the vertical direction, slow in the horizontal direction) is a characteristic of the quantum evolution of the BEC. Images are 1.5 mm high and separated in time by 2 ms.

Figure 2. Diffraction of a BEC by a pulsed standing wave. The image shows the condensate density distribution after a free expansion that allows the momentum components created in the diffraction process to separate spatially.



The standing wave grating shown in Figure 2 can be used as the beamsplitter in a simple Mach-Zehnder-type interferometer (Figure 3), but the splitting time in this geometry is limited to much less than one second because the falling condensate soon hits the bottom of the apparatus. One can do considerably better by making use of the important fact that atoms, unlike photons, can be brought to rest, thereby allowing for very long measurement times. Because our stationary condensate interferometer design[1] has some similarities to light interferometers based on optical fibers, it is natural to refer to it as a condensate waveguide interferometer.

Implementation

Figure 4 illustrates the general principle of waveguide interferometry. The initial state is the condensate confined in the ground state of a thin, cylindrically symmetric harmonic waveguide potential. The potential is then deformed adiabatically into two separated waveguides (Step 1) forming a two-dimensional, double-well potential. In this process, the condensate wavefunction evolves into the symmetric ground state of this potential. Next (Step 2), the perturbation, $V(t)$, under study is applied to one arm of the interferometer for time, τ, introducing a phase shift, ϕ, between the two arms. The resulting wavefunction can then be written in terms of the double-well eigenstates as a superposition of the degenerate symmetric and anti-symmetric ground states. The two arms of the interferometer are now overlapped by adiabatically transforming the potential back to the original single well. In this process (Step 3), the symmetric ground state of the double-well potential returns to the ground state of the single-well potential, and the anti-symmetric double-well state becomes the lowest-energy state of the single well with odd parity, i.e., the first excited state. The output ports of this interferometer in time are therefore the ground state and a first excited state of the waveguide. We present a full quantum-mechanical analysis of this interferometer in Reference 2. The process described above could also be realized as an interferometer in space using waveguides, which physically divide and recombine—in which case the device would resemble an optical fiber interferometer.

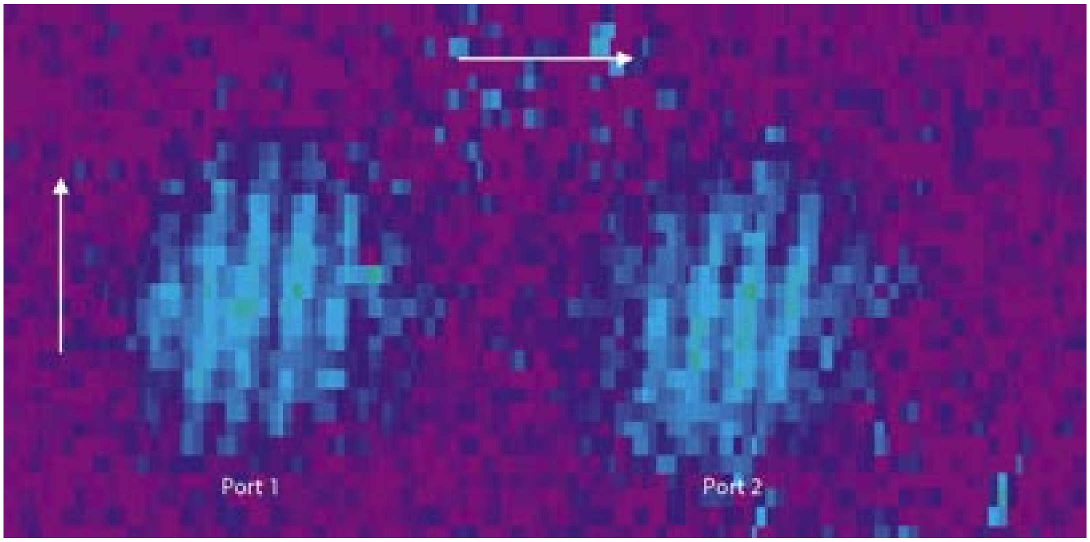


Figure 3. Interferometer fringes formed at the output ports of a freefall Mach-Zehnder condensate interferometer using standing-wave light pulses as beamsplitters.

We are exploring two complementary implementations of the waveguide interferometer—one based on magnetic forces and the other using the optical dipole force exerted by a far-detuned laser beam. The magnetic waveguide configuration consists of two long wires carrying currents in the same direction with a superimposed constant bias magnetic field applied parallel to the plane of the wires.[2] A waveguide for weak-field-seeking atoms (such as the F = 2, m = 2 ground-state atoms in our condensate) exists where the field is zero. We have shown that there are in general two such regions and that at a critical value of the bias field these two regions merge into a single waveguide. Increasing the bias field then splits the potential symmetrically into two, forming a beamsplitter. A full quantum mechanical analysis of this system can be found in our paper[2] along with a discussion of readout techniques—simple direct imaging of the condensate wavefunction is adequate, but there are better alternatives based on further manipulation of the potential.

The optical waveguide interferometer will make use of the optical dipole force, which pushes an atom towards a region of high intensity in a focused laser beam detuned below the atomic resonance. A low-power beam from an infrared diode laser can form a waveguide trap that confines a condensate for several seconds with negligible spontaneous emission. Radial trapping frequencies in such a trap are typically several kilohertz. This simple potential can be manipulated by scanning the laser beam through space at a much higher frequency (e.g., megahertz) than the trap frequency so that the condensate sees only the time-averaged potential. This promises to be a simple, yet powerful and flexible, approach to modifying the potential. A beamsplitter can be realized by passing the laser beam through an acousto-optic modulator used as a deflector to switch the beam back and forth between two positions whose separation increases

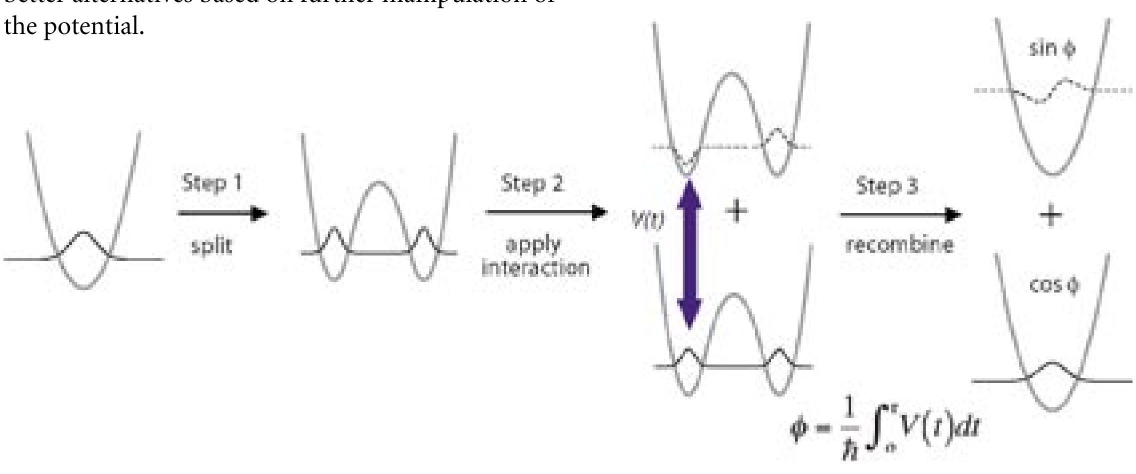


Figure 4. The waveguide interferometer.

slowly. The resulting time-averaged potential evolves into a double well. The scheme extends easily to more complicated geometries, such as dual interferometers for measuring gravity gradients, or to a potential that alternates between horizontal and vertical splitting to suppress systematic effects in a measurement of ***g***.

Conclusion

The sensitivity computed above is based on treating the condensate as a simple coherent matter wave in which each atom occupies the same single-particle state and interactions between atoms are negligible. Although this is the simplest regime in which to work initially, it should be possible to enhance the sensitivity by several orders of magnitude by harnessing the many-body nature of the condensate. The interactions between atoms in the condensate can be used to engineer exotic entangled states in which the measurement uncertainty scales with atom number N as 1/N, instead of the classical scaling factor $1/\sqrt{N}$. Not surprisingly, this enhanced sensitivity comes with a price, which in this case is a decrease in robustness to perturbations from the environment. The open problem of finding the optimal exotic states and devising techniques to create them in the laboratory is currently the subject of research by our T Division colleagues Diego Dalvit, Eddy Timmermans, and Daniel Steck.

References

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2. E.A. Hinds, C.J. Vale, and M.G. Boshier, "Two-wire waveguide and interferometer for cold atoms," *Physical Review Letters* **86**, 1462, (2001).

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